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# Space Exploration and Human Expansion Beyond Earth: Current Status, Technological Challenges, And Future Prospects

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**ABSTRACT:** Space exploration represents one of humanity's most significant scientific and technological achievements, integrating advances in physics, astronomy, aerospace engineering, materials science, robotics, and computational technologies. Since the launch of Sputnik 1 in 1957, space activities have evolved from early orbital experiments and crewed lunar missions into a multidisciplinary enterprise involving planetary exploration, space-based observatories, reusable launch vehicles, commercial satellite infrastructure, and prospective extraterrestrial resource utilization. This review critically examines the historical development, current technological capabilities, scientific achievements, and long-term prospects of space exploration. Particular attention is given to lunar exploration, Mars missions, asteroid sample-return programs, exoplanet observations, advanced propulsion systems, autonomous robotics, radiation protection, and in-situ resource utilization. The review also evaluates major barriers to sustained human presence beyond Earth, including transportation costs, biological risks, limited energy resources, environmental sustainability, and the growing problem of orbital debris. Emerging technologies, such as high-efficiency electric propulsion, artificial intelligence, advanced functional materials, and closed-loop life-support systems, are discussed in relation to their technological maturity and potential contributions. Finally, the opportunities for emerging space nations, particularly Vietnam, are considered within the broader framework of international collaboration and sustainable space development. The analysis suggests that the future of space exploration will depend not only on advances in transportation and scientific instrumentation but also on the integration of reliable autonomous systems, resource-efficient technologies, and internationally coordinated governance.

**KEYWORDS:** Space exploration, lunar exploration, Mars exploration, aerospace technology, electric propulsion, in-situ resource utilization, autonomous robotics, space sustainability.

## 1. INTRODUCTION

Space exploration has fundamentally transformed scientific understanding of the Earth, the Solar System, and the wider Universe. The development of artificial satellites, interplanetary spacecraft, and space-based astronomical observatories has enabled direct investigations of environments that were previously accessible only through theoretical models and ground-based observations.

The early space age was characterized by major technological milestones, including the launch of Sputnik 1 in 1957, the first human spaceflight in 1961, and the Apollo 11 lunar landing in 1969. These achievements established the technological foundations for orbital navigation, spacecraft propulsion, life-support systems, and human operations beyond Earth's atmosphere.

Over subsequent decades, space exploration expanded from short-duration missions to sustained orbital operations, robotic planetary investigations, and increasingly sophisticated astronomical observations. The International Space Station has supported research on biological adaptation, microgravity physics, and human health during prolonged spaceflight. The NASA Twins Study, for example, demonstrated that long-duration spaceflight is associated with complex physiological and molecular responses, emphasizing the need for integrated biomedical monitoring during future exploration missions (Garrett-Bakelman et al., 2019).

Robotic missions have also provided fundamental evidence concerning the geological and environmental evolution of other planetary bodies. Investigations at Gale crater revealed ancient fluvial and lacustrine environments on Mars that could have supported microbial life under suitable conditions (Grotzinger et al., 2014). The detection of preserved organic compounds in

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Martian sedimentary rocks further demonstrated the importance of combining geological, chemical, and astrobiological investigations (Eigenbrode et al., 2018).

Meanwhile, astronomical observations have expanded the search for potentially habitable worlds. The discovery of seven approximately Earth-sized planets orbiting TRAPPIST-1 demonstrated the scientific value of studying compact planetary systems around ultracool dwarf stars (Gillon et al., 2017). Advances in space-based spectroscopy now provide increasingly powerful methods for investigating planetary atmospheres and the early evolution of galaxies.

Despite these achievements, the transition from exploratory missions to sustained extraterrestrial operations remains technologically demanding. High transportation costs, exposure to ionizing radiation, limited access to local resources, and the complexity of autonomous systems constitute major obstacles. In addition, the accumulation of orbital debris threatens the long-term sustainability of near-Earth space activities (Kessler & Cour-Palais, 1978).

This review aims to critically assess the current state of space exploration, identify technological and scientific limitations, and examine the opportunities associated with emerging aerospace technologies. It further considers how developing countries can contribute through targeted research in satellite engineering, materials science, sensing technologies, and computational modeling.

## 2. HISTORICAL DEVELOPMENT AND EVOLUTION OF SPACE EXPLORATION

### 2.1. From early spaceflight to interplanetary exploration

The development of modern astronautics was enabled by the convergence of classical mechanics, propulsion engineering, materials science, and automatic control. Early orbital missions established the practical feasibility of operating artificial objects beyond Earth's atmosphere, while subsequent crewed missions demonstrated the possibility of human survival and controlled operations in space.

The fundamental requirement for orbital flight can be expressed, for a circular orbit, as (1):

$$v_{orb} = \sqrt{\frac{GM}{r}} \quad (1)$$

where G is the gravitational constant, M is the mass of the central body, and r is the orbital radius.

For a spacecraft in low Earth orbit, the characteristic orbital velocity is approximately 7.8 km/s. Achieving orbit, however, requires additional velocity increments to compensate for gravitational losses, aerodynamic drag, and trajectory constraints. The ideal rocket equation is expressed as (2):

$$\Delta v = I_{sp} g_0 \ln\left(\frac{m_0}{m_f}\right) \quad (2)$$

where $I_{sp}$ denotes specific impulse, $g_0$ is standard gravitational acceleration, and $m_0$ and $m_f$ represent the initial and final spacecraft masses, respectively. These physical relationships explain why propulsion efficiency, structural mass, and propellant selection remain central considerations in mission design. Advances in propulsion systems have subsequently expanded the feasibility of robotic missions to distant planets and smaller Solar System bodies (Mazouffre, 2016; Lev et al., 2019; Brophy, 2022).

### 2.2. Human spaceflight and orbital research infrastructure

Human spaceflight has evolved from short-duration missions into sustained orbital operations. Space stations provide controlled environments for studying physiological adaptation, fluid dynamics, materials processing, and biological systems under microgravity conditions.

One of the most important scientific questions concerns the long-term consequences of exposure to microgravity and space radiation. Garrett-Bakelman et al. (2019) reported molecular, physiological, and cognitive observations from the NASA Twins Study, providing evidence that spaceflight produces complex biological responses that may persist after returning to Earth.

These findings have important implications for future lunar and Martian missions. In particular, they emphasize the need for reliable environmental monitoring, radiation shielding, exercise countermeasures, and integrated medical support.

From an engineering perspective, sustained orbital operations have also demonstrated the importance of modular spacecraft design, redundant systems, docking technologies, and international coordination. Such experience provides an operational foundation for future missions beyond low Earth orbit.

### 2.3. Commercialization and reusable launch systems

The increasing participation of commercial organizations has transformed the structure of the space sector. Private companies now contribute to launch services, satellite manufacturing, orbital transportation, and the development of infrastructure for scientific and commercial applications.

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Reusable launch vehicles represent a particularly significant technological development because they can reduce the number of newly manufactured components required for repeated missions. Nevertheless, the economic advantages of reusability depend on refurbishment costs, operational frequency, vehicle reliability, and the payload penalty associated with recovery.
The transition toward commercially sustainable space transportation should therefore be evaluated through life-cycle cost analysis rather than launch price alone.

Furthermore, increased launch accessibility introduces additional challenges, including orbital congestion, atmospheric emissions, and spacecraft end-of-life management. Consequently, commercial expansion must be accompanied by appropriate technical standards and environmental governance (Barentine et al., 2023; Venkatesan, 2023).

## 3. CURRENT STATUS OF PLANETARY AND DEEP-SPACE EXPLORATION

### 3.1. Lunar exploration and the development of extraterrestrial infrastructure

The Moon has regained strategic importance as a potential platform for scientific research, technological demonstration, and future human operations beyond Earth.
Unlike short-duration exploratory missions, the establishment of sustained lunar infrastructure requires reliable energy generation, thermal management, radiation protection, water extraction, and resource-efficient construction technologies.

One of the most significant scientific developments has been the identification of water-related materials on the lunar surface. Li et al. (2018) reported direct evidence of surface-exposed water ice in lunar polar regions. Subsequently, Honniball et al. (2021) identified molecular water on the sunlit lunar surface through infrared observations.
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These findings are scientifically important because water could potentially support human consumption, oxygen production, and propellant manufacturing. However, the existence of lunar water does not establish its immediate economic accessibility.
The feasibility of extraction depends on ice concentration, regolith properties, excavation requirements, thermal conditions, energy availability, and processing efficiency. Moreover, permanently shadowed regions may impose severe operational constraints on mechanical equipment and robotic systems.

Future lunar infrastructure will therefore require the integration of geological exploration, robotic excavation, resource processing, and autonomous environmental control.
Research gap. Although lunar water has been detected, uncertainty remains concerning recoverable reserves, extraction energy requirements, equipment durability, and the reliability of integrated resource-processing systems under actual lunar conditions.

### 3.2. Mars exploration and planetary habitability

Mars remains a principal target of planetary exploration because its geological record preserves evidence of past environmental processes that may have supported habitable conditions.

Robotic missions have substantially improved understanding of Martian sedimentology, mineralogy, atmospheric evolution, and surface chemistry.
Grotzinger et al. (2014) demonstrated that the Yellowknife Bay region of Gale crater once contained a fluvial–lacustrine environment with chemical conditions potentially suitable for microbial life. This finding established an important distinction between present-day surface conditions and ancient Martian environments.

Eigenbrode et al. (2018) subsequently identified organic matter preserved in approximately 3-billion-year-old sedimentary rocks. Although these observations are consistent with the preservation of carbon-bearing compounds, they do not establish biological origins.
The distinction between habitability, organic chemistry, and direct evidence of life is fundamental to astrobiology. An environment may have supported life without necessarily having hosted biological organisms.

Mars exploration also provides an opportunity to investigate the technological feasibility of producing essential resources locally. The carbon-dioxide-rich atmosphere represents a potential feedstock for oxygen production, while subsurface water-bearing materials may support future resource extraction.

Research gap. The principal challenge is transitioning from small-scale demonstrations and geological assessments to integrated systems capable of supplying reliable quantities of oxygen, water, and other resources for sustained human operations.

### 3.3. Asteroid exploration and sample-return missions

Asteroids preserve information about the formation and early evolution of the Solar System. Their mineralogical, isotopic, and organic compositions provide evidence concerning the chemical processes that preceded planetary formation.

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Sample-return missions are particularly valuable because laboratory instruments on Earth can achieve analytical precision and methodological diversity beyond those available on spacecraft.

The study of extraterrestrial samples may also contribute to understanding the distribution of organic compounds and volatile materials throughout the early Solar System.

From an engineering perspective, asteroid exploration presents distinctive challenges. Weak gravitational fields complicate spacecraft navigation, surface contact, material collection, and mechanical anchoring.

Although asteroid mining has attracted commercial interest, large-scale resource extraction remains technologically immature. The economic feasibility of such activities depends on resource concentration, processing requirements, transportation costs, and the intended location of resource consumption.

Research gap. Reliable models are still needed to connect asteroid composition and mechanical properties with excavation performance, resource recovery, and mission-level economic feasibility.

### 3.4. Space telescopes and the search for habitable worlds

Space-based observatories have significantly expanded the capabilities of modern astronomy by enabling observations across spectral regions that are partially or completely inaccessible from Earth's surface. The discovery of the TRAPPIST-1 planetary system illustrates the importance of high-precision photometric observations for identifying potentially terrestrial exoplanets (Gillon et al., 2017). However, planetary radius and orbital position alone are insufficient to establish habitability. Atmospheric composition, stellar activity, surface pressure, planetary magnetic environments, and geological evolution must also be considered. De Wit et al. (2018) demonstrated the value of atmospheric reconnaissance for terrestrial exoplanets, while subsequent spectroscopic investigations have placed additional constraints on atmospheric scenarios. These studies highlight a fundamental methodological challenge: the interpretation of planetary spectra is often affected by degeneracies between atmospheric composition, clouds, aerosols, and thermal structure.

Research gap. Future investigations require improved atmospheric retrieval methods, more comprehensive laboratory spectroscopy, and physically consistent models connecting atmospheric chemistry with planetary evolution.

## 4. KEY TECHNOLOGIES ENABLING FUTURE SPACE EXPLORATION

### 4.1. Advanced propulsion systems

Propulsion technology determines the feasibility, duration, payload capacity, and energy requirements of space missions. Chemical propulsion remains essential for launch operations and high-thrust maneuvers. However, its performance is constrained by the chemical energy stored in propellants and the mass required to achieve large velocity increments. Electric propulsion offers an alternative for in-space operations by accelerating charged particles through electrostatic or electromagnetic processes. Mazouffre (2016) reviewed the fundamental principles and major classes of electric propulsion, including ion thrusters, Hall-effect thrusters, and other plasma-based systems. The review emphasized the high specific impulse achievable with electric propulsion, together with the limitations imposed by power availability and relatively low thrust.

Lev et al. (2019) further examined the technological and commercial expansion of electric propulsion, demonstrating its growing importance across multiple spacecraft applications. Brophy (2022) discussed its transition from experimental technology to widespread operational use.

For an idealized propulsion system, thrust may be approximated as (3):

$$F = \overset{*}{m} v_e \qquad (3)$$

where $\overset{*}{m}$ represents the propellant mass-flow rate and $v_e$ is the effective exhaust velocity.

The specific impulse is defined as (4):

$$I = \frac{F}{\overset{*}{m} g_0} \qquad (4)$$

Although high specific impulse reduces propellant consumption for a specified velocity increment, electric propulsion does not necessarily shorten mission duration. Low thrust may require prolonged acceleration and trajectory optimization. Future developments will depend on advances in plasma confinement, power-processing electronics, thermal management, and high-power energy systems.

Research gap. The major limitation for high-power electric propulsion is the integration of efficient thrusters with lightweight, reliable electrical power generation and heat-rejection systems.

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### 4.2. Advanced materials and radiation protection

Spacecraft materials must withstand mechanical loading, thermal cycling, vacuum exposure, energetic particles, and long-term environmental degradation. Lightweight composites, high-temperature alloys, advanced ceramics, and multifunctional coatings can contribute to improved structural efficiency and operational reliability. Radiation protection represents a particularly important challenge for deep-space missions. Unlike low Earth orbit, where Earth's magnetic environment provides partial protection, interplanetary spacecraft are exposed to galactic cosmic rays and solar energetic particles. Durante and Cucinotta (2011) analyzed the physical basis of radiation protection during space travel, emphasizing the complex interactions between energetic charged particles and shielding materials. The effectiveness of shielding depends not only on material density and thickness but also on elemental composition and secondary-particle production. Hydrogen-rich materials are of interest because they can provide favorable shielding characteristics against certain energetic particle populations. Nevertheless, no single shielding material provides complete protection against the full range of space radiation.

Advanced computational techniques, including Monte Carlo particle transport and atomistic materials modeling, can support the design and evaluation of candidate materials.

Research gap. More experimental and computational research is required to establish reliable relationships among radiation exposure, microscopic material damage, structural degradation, and long-term spacecraft performance.

### 4.3. Autonomous robotics and artificial intelligence

Autonomous systems are essential for planetary missions because communication delays limit the feasibility of continuous real-time control from Earth. Robotic spacecraft must perform navigation, environmental sensing, fault detection, and selected scientific operations with varying degrees of independence. Artificial intelligence may improve autonomous navigation, image interpretation, resource management, and scientific target identification. Machine-learning algorithms can also support the detection of anomalies in spacecraft telemetry and the prioritization of observations. However, the adoption of AI in mission-critical operations requires careful consideration of reliability, interpretability, computational constraints, and performance under unfamiliar environmental conditions. A fundamental limitation is that models trained using terrestrial datasets may not generalize reliably to extraterrestrial environments.

Future systems should therefore integrate machine learning with physics-based models, uncertainty estimation, fault-tolerant control, and rigorous verification procedures.

Research gap. The principal challenge is developing autonomous decision-making systems that remain reliable under limited computational resources, delayed communication, incomplete environmental information, and unexpected operational conditions.

### 4.4. In-situ resource utilization

In-situ resource utilization (ISRU) refers to the extraction, processing, and use of materials available at the mission destination. Potential applications include water extraction, oxygen production, propellant synthesis, construction materials, and manufacturing feedstocks.

ISRU is particularly important for sustained lunar and Martian operations because transporting all required resources from Earth imposes substantial mass and cost penalties. On the Moon, water-bearing deposits and oxygen-containing minerals are potential resources. On Mars, atmospheric carbon dioxide and water-bearing geological materials offer possible pathways for producing oxygen and other mission consumables. Nevertheless, the implementation of ISRU requires more than the identification of useful chemical elements. Practical systems must achieve sufficient extraction rates, product purity, operational reliability, and energy efficiency.

The integration of extraction, processing, storage, and distribution systems remains a major engineering challenge.

Research gap. Future work should prioritize integrated ISRU demonstrations that quantify energy consumption, material recovery, system degradation, and operational performance over extended periods.

## 5. MAJOR CHALLENGES TO SUSTAINABLE SPACE EXPLORATION

### 5.1. Economic feasibility and technological reliability

The economic sustainability of space exploration depends on the relationship among mission cost, technical performance, operational risk, and long-term scientific or commercial benefits. Launch costs represent only one component of total mission expenditure. Spacecraft development, environmental testing, ground infrastructure, communication networks, mission operations, and contingency management also contribute substantially to overall costs.

Reusable launch technologies may reduce recurring manufacturing expenditure, but their advantages must be evaluated against refurbishment requirements, recovery infrastructure, and reliability constraints. An additional consideration is the difference

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between commercial space services and scientific exploration. While satellite communications and Earth observation can generate recurring revenue, deep-space scientific missions frequently depend on public investment because their principal benefits are scientific knowledge and technological development rather than immediate financial returns.

Consequently, the economic evaluation of space activities should distinguish between direct commercial profitability, scientific value, strategic infrastructure, and long-term technological spillovers.

### 5.2. Space radiation and human health

The biological consequences of prolonged spaceflight remain a major obstacle to human exploration beyond Earth. Exposure to microgravity affects musculoskeletal function, cardiovascular regulation, fluid distribution, and physiological adaptation. Ionizing radiation introduces additional risks involving DNA damage, cellular dysfunction, and potentially long-term health consequences. The NASA Twins Study demonstrated the complexity of physiological and molecular responses to extended spaceflight (Garrett-Bakelman et al., 2019).

Radiation protection requires an integrated approach combining shielding design, exposure monitoring, mission planning, and medical risk assessment. Durante and Cucinotta (2011) emphasized that the biological effects of energetic heavy ions represent a particularly challenging aspect of deep-space radiation protection. The development of artificial gravity, improved shielding systems, and advanced biomedical countermeasures may contribute to reducing these risks. However, many proposed solutions require further experimental validation.

### 5.3. Orbital debris and environmental sustainability

The rapid growth of satellite constellations has increased concern regarding orbital congestion and the long-term sustainability of near-Earth space activities. Kessler and Cour-Palais (1978) demonstrated that collisions between orbiting objects can produce debris populations that increase the probability of subsequent collisions. This mechanism remains a fundamental concern in orbital debris modeling. The environmental implications extend beyond collision risks. Barentine et al. (2023) examined the cumulative effects of artificial satellites and associated debris on astronomical observations, including changes in night-sky brightness. Venkatesan (2023) emphasized the importance of treating orbital space as a shared environment requiring internationally coordinated stewardship. More recently, Elvis et al. (2024) discussed the need to integrate environmental responsibility, ethical considerations, and policy development into the future expansion of space activities.

Effective mitigation requires reliable tracking, collision avoidance, spacecraft passivation, responsible disposal practices, and the development of active debris-removal technologies.

### 5.4. Planetary protection and extraterrestrial environmental integrity

Planetary exploration introduces the possibility of biological and chemical contamination between Earth and other celestial bodies. Forward contamination occurs when terrestrial organisms or biological materials are transported to extraterrestrial environments. Backward contamination refers to the potential introduction of extraterrestrial material into Earth's biosphere. These concerns are especially relevant to missions involving environments that may preserve evidence of past or present life. Planetary protection measures must therefore be incorporated into spacecraft design, sample handling, sterilization procedures, and mission operations. The development of extraterrestrial resource industries also raises questions concerning environmental disturbance, scientific preservation, and the equitable use of shared space resources.

A sustainable exploration framework must balance scientific access, economic development, planetary protection, and international responsibilities.

## 6. FUTURE PROSPECTS AND EMERGING RESEARCH DIRECTIONS

### 6.1. Permanent lunar research infrastructure

Future lunar exploration may evolve toward semi-permanent or continuously operated research facilities. Potential scientific applications include lunar geology, low-frequency radio astronomy, materials testing, and technology demonstrations for deep-space operations. The availability of water-related resources could support life-support systems and propellant production, although extraction feasibility remains uncertain (Li et al., 2018; Honniball et al., 2021). Long-term infrastructure will require reliable power generation, energy storage, thermal regulation, and robotic construction capabilities.

A particularly important research direction is the development of modular infrastructure that can be expanded incrementally while minimizing dependence on terrestrial resupply.

### 6.2. Human exploration of Mars

Human missions to Mars represent a substantially greater engineering challenge than operations in low Earth orbit or on the Moon. Long transportation times, communication delays, radiation exposure, and limited opportunities for emergency return

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require highly reliable and autonomous spacecraft systems. Sustained operations would depend on integrated life-support systems, local resource processing, habitat protection, and medical autonomy. The most realistic near-term pathway involves progressive technological demonstrations rather than immediate establishment of a self-sustaining settlement.

### 6.3. Space-based manufacturing and extraterrestrial resource utilization

Manufacturing beyond Earth could eventually support the production of structural components, replacement parts, scientific equipment, and infrastructure. Potential approaches include additive manufacturing, robotic assembly, and processing of locally available materials. However, the technical feasibility of space-based manufacturing depends on material properties, energy availability, process control, and quality assurance under reduced-gravity conditions. A central research question is whether local manufacturing can reduce total mission mass and cost after accounting for equipment transportation, energy systems, maintenance, and operational complexity.

### 6.4. Next-generation propulsion and deep-space missions

Future deep-space exploration may benefit from higher-power electric propulsion, nuclear thermal propulsion, nuclear electric propulsion, and advanced sail technologies. These approaches differ significantly in physical principles, achievable thrust, power requirements, and technological readiness. Electric propulsion is already established for several spacecraft applications, whereas many higher-power and advanced propulsion concepts remain at the research or development stage (Mazouffre, 2016; Brophy, 2022). The development of reliable space power systems is likely to be as important as improvements in propulsion efficiency.

### 6.5. Astrobiology and the search for extraterrestrial life

The search for life beyond Earth remains a major scientific motivation for planetary exploration. Future investigations will focus on environments with evidence of liquid water, chemical energy sources, and potentially preserved biological signatures. Mars, icy ocean worlds, and selected exoplanets are important targets for astrobiological research. However, detecting organic molecules or potentially habitable conditions is not equivalent to detecting life.

Reliable biosignature identification requires multiple independent lines of evidence, careful consideration of abiotic alternatives, and robust analytical methods.

### 6.6. Quantum technologies and advanced scientific instrumentation

Quantum sensing, atomic clocks, and precision interferometry may improve spacecraft navigation, gravitational measurements, and fundamental physics experiments. Space-based instruments can also provide environments for testing physical theories under conditions that are difficult to reproduce in terrestrial laboratories. The direct detection of gravitational waves by Abbott et al. (2016) demonstrated the scientific importance of precision measurement technologies and opened new observational possibilities in astrophysics. Future space-based gravitational-wave observatories may extend observations into frequency ranges inaccessible to existing ground-based detectors.

## 7. OPPORTUNITIES FOR EMERGING SPACE NATIONS: THE CASE OF VIETNAM

### 7.1. Small satellites and Earth-observation technologies

For emerging space nations, small satellites represent an accessible pathway toward developing aerospace engineering capabilities. Applications include environmental monitoring, agricultural assessment, disaster management, telecommunications, and scientific observation.

Developing domestic expertise in satellite subsystems, sensor integration, telemetry, and data processing can also strengthen related industrial sectors.

### 7.2. Advanced materials and computational modeling

Materials science provides a promising opportunity for participation in international space research. Potential research topics include radiation-resistant semiconductors, lightweight structural materials, thermal protection coatings, photovoltaic materials, and advanced sensing devices. First-principles calculations based on density functional theory can contribute to the screening of candidate materials by predicting structural stability, electronic properties, optical response, and selected defect characteristics.

Nevertheless, electronic-structure calculations alone cannot establish spacecraft qualification. Experimental validation under thermal, vacuum, mechanical, and radiation conditions remains essential.

### 7.3. Autonomous systems and intelligent sensing

Expertise in embedded systems, robotics, computer vision, and artificial intelligence can support the development of autonomous technologies relevant to space missions. Research universities may contribute through low-cost experimental platforms,

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digital twins, fault-detection algorithms, and integrated sensor systems. Such research can generate both space-related and terrestrial applications.

### 7.4. International cooperation and workforce development

International partnerships are important for accessing specialized facilities, scientific datasets, and advanced engineering expertise. A sustainable national strategy should prioritize carefully selected areas in which domestic institutions can develop competitive capabilities. For Vietnam, these areas may include satellite data analysis, semiconductor materials, remote sensing, embedded electronics, autonomous control, and computational physics. Long-term success will depend on coordinated investment in research infrastructure, graduate education, industry partnerships, and international scientific collaboration.

## 8. CRITICAL DISCUSSION AND RESEARCH PRIORITIES

The literature indicates that space exploration is undergoing a transition from mission-specific technological demonstrations toward increasingly integrated infrastructure and service-oriented systems. However, technological progress is uneven. Certain capabilities, including orbital satellite operations, robotic planetary exploration, and selected electric propulsion technologies, are well established. Other capabilities, such as large-scale extraterrestrial resource extraction and sustained human settlements, remain largely developmental. A central challenge is the integration of technologies that have been demonstrated individually but not yet validated as complete operational systems. For example, the identification of lunar water does not guarantee the feasibility of an integrated water-production facility. Similarly, the successful operation of an electric thruster does not independently establish the feasibility of a high-power interplanetary transportation architecture. The distinction between scientific discovery, component-level demonstration, and system-level operational readiness is therefore essential.

**Table 1. Comparative assessment of selected space exploration technologies**

| Technology | Current maturity | Major limitation | Research priority |
|---|---|---|---|
| Reusable launch vehicles | Operational for selected systems | Refurbishment, reliability, payload trade-offs | Life-cycle optimization |
| Electric propulsion | Operational | Power availability and low thrust | High-power integration |
| Lunar water extraction | Resource detection and early demonstrations | Recovery rate and energy demand | Integrated ISRU systems |
| Martian oxygen production | Demonstrated at small scale | Scale-up and reliability | Continuous resource production |
| Autonomous planetary robotics | Operational with limited autonomy | Uncertainty and fault handling | Verified autonomous decisions |
| Human deep-space habitats | Developmental | Radiation, life support, resupply | Integrated long-duration validation |
| Asteroid resource extraction | Early-stage | Excavation and economic feasibility | Robotic processing demonstrations |
| Active orbital debris removal | Demonstration and development | Capture, cost, coordination | Safe scalable removal |

Maturity classifications are qualitative assessments of demonstrated capabilities, not standardized technology readiness level (TRL) scores.

### 8.1. Integration of propulsion and energy technologies

Future exploration architectures should be evaluated using system-level metrics rather than isolated subsystem performance. High-specific-impulse propulsion may reduce propellant requirements, but its benefits must be balanced against the mass and complexity of electrical power systems. Likewise, nuclear energy technologies may improve mission capability while introducing additional requirements concerning shielding, thermal management, safety, and regulatory oversight.

### 8.2. Materials reliability under extraterrestrial conditions

The durability of materials under combined radiation, temperature cycling, vacuum exposure, and mechanical stress remains insufficiently understood for many long-duration applications. Future research should combine atomistic simulations, multiscale materials modeling, accelerated environmental testing, and in-space validation.

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### 8.3. Sustainability and international governance

Space sustainability must be incorporated into mission planning from the earliest design stages. Orbital debris management, planetary protection, environmental impact assessment, and equitable access to space resources are interconnected challenges. International coordination is particularly important because the consequences of orbital collisions and environmental degradation extend beyond individual operators and national jurisdictions.

### 8.4. Priorities for future research

The most consequential scientific and engineering priorities include improving propulsion efficiency, developing lightweight and reliable power systems, establishing integrated ISRU capabilities, advancing radiation protection, and increasing the autonomy of robotic systems.

Progress should be evaluated using experimentally demonstrated performance, uncertainty analysis, and long-term operational reliability rather than projected technological potential alone.

## 9. CONCLUSIONS

Space exploration has evolved into a multidisciplinary scientific and technological enterprise with implications extending far beyond traditional aerospace engineering. Major advances in propulsion, planetary science, astronomical observation, autonomous robotics, and materials engineering have significantly expanded humanity's ability to investigate the Solar System and the wider Universe. Nevertheless, sustained human operations beyond Earth remain constrained by transportation requirements, radiation exposure, resource limitations, technological reliability, and economic feasibility. The future of space exploration will depend on integrating advanced propulsion, autonomous systems, reliable energy technologies, resource-efficient manufacturing, and robust life-support infrastructure. Equally important, the expansion of space activities must be accompanied by responsible environmental management and internationally coordinated governance. For emerging space nations, participation in the space sector does not necessarily require immediate investment in large launch vehicles or crewed exploration programs. Targeted development of satellite technologies, advanced materials, sensing systems, computational modeling, and autonomous control offers a more practical foundation for long-term scientific and technological contributions. Ultimately, successful expansion beyond Earth should be measured not only by the ability to reach distant destinations but also by the capacity to operate safely, sustainably, and scientifically productively over extended periods.

## REFERENCES

1. Abbott, B. P., et al. (2016). Observation of gravitational waves from a binary black hole merger. Physical Review Letters, 116(6), 061102. https://doi.org/10.1103/PhysRevLett.116.061102
2. Barentine, J. C., Venkatesan, A., Heim, J., Lowenthal, J., Kocifaj, M., & Bará, S. (2023). Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise. Nature Astronomy, 7, 252–258. https://doi.org/10.1038/s41550-023-01904-2
3. Brophy, J. R. (2022). Perspectives on the success of electric propulsion. Journal of Electric Propulsion, 1, Article 9. https://doi.org/10.1007/s44205-022-00011-0
4. Cilliers, J., Hadler, K., & Rasera, J. (2023). Toward the utilisation of resources in space: Knowledge gaps, open questions, and priorities. npj Microgravity, 9, Article 22. https://doi.org/10.1038/s41526-023-00274-3
5. Durante, M., & Cucinotta, F. A. (2011). Physical basis of radiation protection in space travel. Reviews of Modern Physics, 83(4), 1245–1281. https://doi.org/10.1103/RevModPhys.83.1245
6. Eigenbrode, J. L., et al. (2018). Organic matter preserved in 3-billion-year-old mudstones at Gale crater, Mars. Science, 360(6393), 1096–1101. https://doi.org/10.1126/science.aas9185
7. Elvis, M., Jah, M., Nesvold, E., & Suzuki, K. (2024). Shaping the ethical, sustainable and policy-driven future of space exploration. Nature Reviews Materials, 9, 769–772. https://doi.org/10.1038/s41578-023-00636-z
8. Garrett-Bakelman, F. E., et al. (2019). The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight. Science, 364(6436), eaau8650. https://doi.org/10.1126/science.aau8650
9. Gillon, M., et al. (2017). Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. Nature, 542, 456–460. https://doi.org/10.1038/nature21360
10. Grotzinger, J. P., et al. (2014). A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale crater, Mars. Science, 343(6169), 1242777. https://doi.org/10.1126/science.1242777
11. Honniball, C. I., Lucey, P. G., Li, S., Shenoy, S., Orlando, T. M., Hibbitts, C. A., Hurley, D. M., & Farrell, W. M. (2021). Molecular water detected on the sunlit Moon by SOFIA. Nature Astronomy, 5, 121–127. https://doi.org/10.1038/s41550-020-01222-x

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12. Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. Journal of Geophysical Research, 83(A6), 2637–2646. https://doi.org/10.1029/JA083iA06p02637
13. Lev, D., Myers, R. M., Lemmer, K. M., Kolbeck, J., Koizumi, H., & Polzin, K. (2019). The technological and commercial expansion of electric propulsion. Acta Astronautica, 159, 213–227. https://doi.org/10.1016/j.actaastro.2019.03.058
14. Levchenko, I., et al. (2020). Perspectives, frontiers, and new horizons for plasma-based space electric propulsion. Physics of Plasmas, 27(2), 020601. https://doi.org/10.1063/1.5109141
15. Li, S., Lucey, P. G., Milliken, R. E., Hayne, P. O., Fisher, E., Williams, J.-P., Hurley, D. M., & Elphic, R. C. (2018). Direct evidence of surface exposed water ice in the lunar polar regions. Proceedings of the National Academy of Sciences, 115(36), 8907–8912. https://doi.org/10.1073/pnas.1802345115
16. Lorenz, R. (1991). Small satellites and electric propulsion—A review. The Aeronautical Journal, 95(946), 204–213. https://doi.org/10.1017/S0001924000023915
17. Mazouffre, S. (2016). Electric propulsion for satellites and spacecraft: Established technologies and novel approaches. Plasma Sources Science and Technology, 25(3), 033002. https://doi.org/10.1088/0963-0252/25/3/033002
18. Mazouffre, S., & Delbosq, V. (2025). Electron polytropic exponent in the plasma plume of a high power Hall thruster firing with xenon and krypton. Journal of Electric Propulsion, 4, Article 50. https://doi.org/10.1007/s44205-025-00153-x
19. Rapp, D., & Inglezakis, V. J. (2024). Mars in situ resource utilization (ISRU) with focus on atmospheric processing for near-term application—A historical review and appraisal. Applied Sciences, 14(2), 653. https://doi.org/10.3390/app14020653
20. Starr, S. O., & Muscatello, A. C. (2020). Mars in situ resource utilization: A review. Planetary and Space Science, 182, 104824. https://doi.org/10.1016/j.pss.2019.104824
21. Venkatesan, A. (2023). Stewardship of space as shared environment and heritage. Nature Astronomy, 7, 236. https://doi.org/10.1038/s41550-023-01915-z
22. Zhang, P., et al. (2023). Overview of the lunar in situ resource utilization techniques for future lunar missions. Space: Science & Technology, Article 0037. https://doi.org/10.34133/space.0037
23. Zieba, S., et al. (2023). No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c. Nature. https://doi.org/10.1038/s41586-023-06232-z
24. Boyd, I. D. (2005). Numerical modeling of spacecraft electric propulsion thrusters. Progress in Aerospace Sciences, 41(8), 669–687. https://doi.org/10.1016/j.paerosci.2006.01.001
25. Cichocki, F., Taccogna, F., & Garrigues, L. (2022). Numerical simulations of plasma thrusters and/or related technologies. Frontiers in Physics, 10. https://doi.org/10.3389/fphy.2022.1074459
26. Luger, R., et al. (2017). A seven-planet resonant chain in TRAPPIST-1. Nature Astronomy, 1, Article 0129. https://doi.org/10.1038/s41550-017-0129
27. de Wit, J., et al. (2018). Atmospheric reconnaissance of the habitable-zone Earth-sized planets orbiting TRAPPIST-1. Nature Astronomy, 2, 214–219. https://doi.org/10.1038/s41550-017-0374-z
28. Gross, C., et al. (2024). Prospecting in-situ resources for future crewed missions to Mars. Acta Astronautica, 223, 15–24. https://doi.org/10.1016/j.actaastro.2024.07.003
29. Long-Fox, J. M., Campins, H., & Britt, D. T. (2026). A review of technologies for lunar science, exploration, resources, and settlement. Planetary and Space Science, 270, 106229. https://doi.org/10.1016/j.pss.2025.106229
30. Tománek, R., & Hospodka, J. (2018). Reusable launch space systems. MAD—Magazine of Aviation Development, 6(2). https://doi.org/10.14311/MAD.2018.02.02

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